



## Environmental tobacco smoke in an unrestricted smoking workplace: area and personal exposure monitoring

ROGER A. JENKINS,<sup>a</sup> MICHAEL P. MASKARINEC,<sup>a</sup> RICHARD W. COUNTS,<sup>b</sup> JOHN E. CATON,<sup>a</sup>  
BRUCE A. TOMKINS<sup>a</sup> AND RALPH H. ILGNER<sup>a</sup>

<sup>a</sup>Chemical and Analytical Sciences Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, Tennessee 37831-6120

<sup>b</sup>Computer Science and Mathematics Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, Tennessee 37831-6120

The objective of this investigation was to determine the extent of areal and day-to-day variability of stationary environmental tobacco smoke (ETS) concentrations in a single large facility where smoking was both prevalent and unrestricted, and to determine the degree of daily variation in the personal exposure levels of ETS constituents in the same facility. The subject facility was a relatively new four-story office building with an approximate volume of 1.3 million ft<sup>3</sup>. The exchange of outside air in the building was determined to be between 0.6 and 0.7 air changes per hour. Eighty-seven area samples (excluding background) were collected at 29 locations over the course of 6 days of sampling. Locations included offices and cubicles occupied by smokers and nonsmokers, common areas, and the computer and mail rooms. Twenty-four nonsmoking subjects wore personal sampling systems to collect breathing zone air samples on each of 3 days in succession. This generated a total of seventy-two 8-h time-weighted average (TWA) personal exposure samples. In all samples, respirable suspended particulate matter, ultraviolet light-absorbing and fluorescing particulate matter, solanesol, nicotine, and 3-ethenyl pyridine were determined. With the exception of a few locations, tobacco-specific airborne constituents were determined in all samples. Not surprisingly, areas with the highest ETS constituent concentrations were offices and cubicles of smokers. Median and 95th percentile concentrations for all area samples, excluding background, were determined to be 1.5 and 8.7  $\mu\text{g}/\text{m}^3$  for nicotine, and 8.2 and 59  $\mu\text{g}/\text{m}^3$  for ETS-specific particles (as solanesol-related particulate matter, Sol-PM), respectively. Personal exposure concentrations of ETS components were similar to those levels found in the area samples (median nicotine and Sol-PM concentrations were 1.24 and 7.1  $\mu\text{g}/\text{m}^3$ , respectively), but the range of concentrations was somewhat smaller. For example, the 95th percentile 8-h TWA nicotine and ETS-specific particle (as Sol-PM) concentrations were 3.58 and 21.9  $\mu\text{g}/\text{m}^3$ , respectively. Intrasubject variation of daily concentrations ranged from 20% to 60%, depending on the component. Self-reported proximity to smokers was supported by higher ETS concentrations determined from the personal monitors, but only to a modest extent. Although smoking was completely unrestricted inside the main office areas of the facility, ETS levels, either areal or from personal exposure measurements, were lower than those estimated by Occupational Safety and Health Administration to be present in such facilities. *Journal of Exposure Analysis and Environmental Epidemiology* (2001) 11, 369–380.

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### Introduction

Exposure to environmental tobacco smoke (ETS) in occupational settings continues to be a subject of considerable interest and regulatory consideration. In 1994, the Occupational Safety and Health Administration (OSHA) proposed severe restrictions on smoking in workplaces (USDOL, 1994). By 1995, 71% of workplaces, as

determined by the International Facility Management Association, had reported some form of smoking restriction, as reported by the Congressional Research Service (Redhead and Rowberg, 1995). As of the end of 1998, 41 states and the District of Columbia restricted smoking in state government worksites, and 20 states and the District of Columbia restricted smoking in private sector worksites (Centers for Disease Control and Prevention, 1999). In a survey taken in 1999, for 17 states and the District of Columbia, it was estimated that the fraction of adults working in a smoke-free environment ranged from 62% to 82% (Centers for Disease Control and Prevention, 2000).

ETS is considered to be a ubiquitous contaminant of indoor air inside any facility where smoking is permitted. Several studies have determined concentrations of tobacco-specific ETS constituents in office buildings, in most cases focusing on obtaining a few samples in each of a variety of locations. Oldaker et al. (1990) reported short-duration (ca.

1. Abbreviations: CO<sub>2</sub>, carbon dioxide; ETS, environmental tobacco smoke; FPM, fluorescing particulate matter; HPLC, high-performance liquid chromatograph; OSHA, Occupational Safety and Health Administration; RSP, respirable suspended particulate matter; Sol-PM, solanesol-related particulate matter; TWA, time-weighted average; UVPM, ultraviolet light-absorbing particulate matter.

2. Address all correspondence to: Dr. Roger A. Jenkins, Mail Stop 6120, Building 4500S, Oak Ridge National Laboratory, Bethel Valley Road, PO Box 2008, Oak Ridge, TN 37831-6120. Tel.: +1-865-574-4871. Fax: +1-865-576-7956. E-mail: jenkinsra@ornl.gov

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1 h) concentrations of nicotine, respirable suspended particulate matter (RSP), and ultraviolet light-absorbing particulate matter (UVP) in more than 125 smoking offices in four major cities. Turner et al. (1992) reported on RSP, nicotine, carbon monoxide, and carbon dioxide (CO<sub>2</sub>) concentrations in "office" areas in nearly 500 locations. Hedge et al. (1994) measured nicotine and other non-tobacco-specific indoor air constituents in 27 office buildings, segregated according to ventilation system. Hammond et al. (1995) measured area levels of ETS nicotine at 60 locations in offices at multiple worksites where smoking was unrestricted. Baek et al. (1997) determined levels of nicotine and other volatile organic compounds in 12 office buildings in Korea, four of which had newly instituted nonsmoking policies. Such studies have produced exceptionally useful information as to the concentrations of constituents likely to contribute to human exposure to ETS. With a few exceptions, however, these studies have not provided information as to the range of concentrations likely to be encountered in a single facility. Vaughan and Hammond (1990) reported nicotine concentrations sampled at *ca.* 20 office locations and 9 public cafeteria/snack bar locations before and following a smoking restriction in a single building. Studies in offices with extensive area measurements of ETS concentrations, coupled with personal monitoring data acquired simultaneously, have been very limited. In a study reported by Sterling et al. (1996), median personal exposure levels of ETS constituents for 25 subjects in two facilities where smoking was not restricted were not statistically different from those of 16 area measurements made in the same facility.

A number of large studies of personal exposure to ETS have been conducted during the last decade in North America, Europe, and Asia (e.g., Heavner et al., 1996; Jenkins et al., 1996; Phillips et al., 1996, 1998). While these studies have included workplace, home, and away-from-work venues, and represent a major advance in our understanding of overall personal exposure to ETS, virtually all of the studies using active personal breathing zone sampling have involved a 24-h "snapshot" of exposure, usually comprised of a single day's measurement (8 and 16 h) in the workplace and away from work, respectively. Virtually no studies have examined the repeatability of personal exposure in any workplace where ETS is a frequently encountered contaminant. Determination of the periodic (e.g., daily) variation in exposures to airborne contaminants is critical to the accurate estimation of the organ distribution of the chemicals and/or associated risk (Whitmyre et al., 1992; Lakind et al., 1999). For exposures associated with specific sources, such as ETS, exposure and associated dose are likely to vary with human activity patterns (e.g., Jenkins et al., 1992; Funk et al., 1998). Currently, the only inputs for risk assessments have been *estimates* of the variability.

The objectives of the study reported here were (a) to determine the extent of areal and day-to-day variability of fixed-location ETS concentrations in a single large facility where smoking was both prevalent and unrestricted, and (b) to determine the degree of daily variation in the personal exposure levels of ETS constituents in the same facility.

## Experimental

### Facility

The target facility was a corporate headquarters building of a US company, located in central North Carolina. Smoking was permitted throughout the building, and was essentially unrestricted, except for the mail and computer rooms. Cigarette, cigar, and pipe smoking were all permitted. The facility had four floors and a modern heating ventilation and air conditioning (HVAC) system that typically features greater use of outside make-up air than many conventional facilities. During occupied hours, the rate of outside air input was constant, irrespective of ambient temperature. The layout of each floor was similar, but not identical. Offices tended to be placed on the outer walls of the building, and cubicles (either 39- or 62-in.-high walls) in the center. The total volume of the building was approximately 1.3 million ft<sup>3</sup>, of which the separately ventilated computer room comprised approximately 75,000 ft<sup>3</sup>. The facility was typically occupied by 300 people, of which 16% was comprised of smokers. This fraction is lower than that of the adult population of North Carolina (Centers for Disease Control and Prevention, 2000), but not out of line with expectations for this occupational group (Pamuk et al., 1998).

### Air Exchange Estimates

To provide an independent estimate of potential air exchange rates during periods of peak building occupancy, a number of CO<sub>2</sub> measurements were made throughout the facility, near the positions of the area sampling pumps. CO<sub>2</sub> was measured using a TSI "Q-Check" Model 8730 handheld meter (TSI, Minneapolis, MN), which had been factory-calibrated. The meter was allowed to equilibrate near the ETS pumps, and the reading was recorded.

### Area Sampling

The sampling equipment for ETS markers and particle phase species was similar to that described by Ogden et al. (1996), and is now commercially available as the Double Take Sampler, manufactured by SKC (Eighty-Four, PA). Two sound-insulated constant-flow pumps are built into a single unit, and were used to collect the vapor phase and particulate phase samples through separate channels. Vapor phase samples were collected using XAD-4 cartridges (Catalog Number S2-0361; SKC) at a rate of

approximately 1.1 l/min. Particulate phase samples were collected using 37-mm Fluoropore filters at a flow rate of 2.2–2.3 l/min, using a BGI-4CP Respirable Dust Cyclone sampling system (available from BGI, Waltham, MA). Particle phase markers determined as part of this study were: RSP (4.0  $\mu\text{m}$  or smaller), UVPM, fluorescing particulate matter (FPM), and solanesol. The filter cassette was fabricated from opaque conductive plastic and aluminum. A cyclone vortex assembly preceded the filter cassette, such that the material collected on the filter was all of respirable (50% cutoff at 4- $\mu\text{m}$  mass median aerodynamic diameter) size. The sampling systems were assembled in a conference room in the building, where no smoking was permitted during the duration of the study, using the following procedure. Preweighed (see below) filters were placed in cassettes identified by bar code labels, that were, in turn, affixed in the sampling head. Vapor phase samples were collected on XAD-4 cartridges and analyzed for nicotine and 3-ethenyl pyridine (3-EP). XAD-4 cartridges were labeled, the glass tips broken off, and installed in the sampling head. Using two mass flow meters, the particulate phase flow was adjusted to 2.2–2.3 l/min, vapor phase flow was adjusted to 1.1 l/min, and both were recorded. When the sampling systems were returned to the conference room at the end of the sampling period, sample durations and flow rates were recorded again. Average flow rates (mean of start and ending) and sampling duration were used to calculate the volume sampled, and thus the ETS marker concentrations.

Sample site selection was influenced by the nature of the different arrangement of cubicles and offices on each floor. Stationary (area) samples were collected in specified locations over the course of 3 days (collection for approximately 8 h at the same location on each of three consecutive days). Sampling was conducted on two of the building's four floors during the first week of sampling, and two during the second week of sampling. Field operations were conducted during the month of January 1999. Measurement on consecutive days provided a measure of the degree of variation in the source and dispersal, and potential exposure concentrations, of ETS. Sampling locations included:

1. Offices occupied by smokers
2. Offices occupied by nonsmokers
3. Cubicles occupied by smokers (high wall/low wall, or both, depending on floor)
4. Cubicles occupied by nonsmokers (high wall/low wall, or both, depending on floor)
5. General or community area (lunchroom)
6. Computer room (background sample; first floor only)
7. The conference room where the samplers were assembled
8. Outdoors (on the roof at the air intake)
9. In the ventilation plenum.

The exact location of the samplers depended on position relative to ventilation system ducts and smoker office/cubicle locations. As a conservative approach, an attempt was made to locate samplers for nonsmoking cubicles/offices at a point that was closest to the most relevant point of human exposure, i.e., at head height for sitting or standing. However, no effort was made to match the location of the area samplers with the primary work locations of the subjects in the personal exposure study (see below).

The collection and counting of cigarette butts or smoking product remnants were attempted, but were not successful. The janitorial staff had been requested to empty ashtrays into a single repository during the evening of each day that the sampling was conducted. However, inspection of the collection process by the sampling team indicated that adherence to the protocol was intermittent, and highly dependent on the individual performing the cleaning. The authors have experienced this same situation in hospitality venues in which other studies have been conducted. Because the actual number of cigarette butts collected would seriously underrepresent the actual number of cigarettes smoked in the facilities, the number of butts that were collected was not reported.

#### *Personal Exposure Sampling*

Determination of personal exposure to ETS components concurrent with the area sample collection comprised a second aspect of the overall study. Twenty-four non-smoking employees were recruited for the study, and provided a gratuity of a restaurant gift certificate by their employer for their participation in the study. Subjects wore a personal sample collection system in their breathing zone (Jenkins et al., 1996) as they went about their workplace duties over an 8.5- to 9-h span on three consecutive days. The pump unit was identical to that used for the area samples, and was worn on the left hip with the aid of a shoulder strap. Subjects wore the systems concurrently with area sample collection on their primary work floor. Subjects were free to move throughout the building in the normal conduct of their job duties.

#### *Analysis of Indoor Air and ETS Components*

Analytical chemical procedures used in this study were identical to those used in our previous studies (e.g., Jenkins et al., 1996; Maskarinec et al., 2000). Vapor phase samples were analyzed for nicotine and 3-EP, according to the method of Ogden (1991). The XAD-4 cartridges were extracted using 1.5 ml ethyl acetate containing 0.5% triethylamine and 8.2  $\mu\text{g}/\text{ml}$  quinoline (internal standard). The analysis was performed using a Hewlett-Packard Model 5890A gas chromatograph equipped with a Model 7673 autosampler, a 30M DB-5 capillary column (0.32 mm i.d., 1.5  $\mu\text{m}$  film thickness), and a nitrogen/phosphorus detector.

Methods used for the determination of particulate phase ETS markers have been described in detail elsewhere (Conner et al., 1990; Ogden and Maiolo, 1992; Ogden et al., 1990). Briefly, RSP was determined by weighing the filters in triplicate on an electrobalance (Cahn) after overnight incubation at 50% humidity. The average of the triplicate determinations was taken as the filter weight. After sampling, the procedure was repeated, and the difference reported as RSP. The remaining particulate phase markers, UVP, FPM, and solanesol were determined after extraction of the filter with 2.0 ml methanol. UVP and FPM were determined simultaneously using a Hewlett-Packard Model 1090 high-performance liquid chromatograph (HPLC) equipped with an autosampler, a short section of 0.2-mm tubing (to replace the column), and sequential diode array and fluorescence detectors. 2,2',4,4'-Tetrahydroxybenzophenone was used as a surrogate standard for the UVP measurement, whereas scopoletin was used for the determination of FPM. Solanesol was determined using a Hewlett-Packard model 1090 HPLC equipped with an autosampler, a Spherisorb-ODS column (4.6 mm i.d., 25 cm long), and a diode array detector operated at 205 nm. The mobile phase was 100% methanol. All values were measured in micrograms per sample, and converted to micrograms per cubic meter using the flow rate and duration data. The particle phase was not analyzed for nicotine because virtually all of the nicotine (95%+) from ETS is acknowledged to be present in the vapor phase (Ogden and Jenkins, 1999).

## Results and discussion

### CO<sub>2</sub> Levels and Building Air Exchange Rates

Over 300 individual measurements were made of ambient CO<sub>2</sub> concentrations during the 2 weeks of the study. The data are summarized in Figure 1, and exhibit the expected trend of increase over the course of the day. Median concentrations in the first few hours of the workday were ca. 125–175 ppm greater than the expected outside ambient levels of ca. 375 ppm. Over the course of the day, CO<sub>2</sub> levels increased somewhat. The maximum measured concentration was 780 ppm, measured in the computer room.

While the HVAC system was designed to handle 73,410 cubic feet per minute (cfm), the outside air input rate was designed to be 16,890 cfm, or an effective fresh air exchange rate of 0.83 air changes per hour (ACH). To provide an independent estimate of the air exchange rate, the rate was estimated through comparison of inside *versus* outside CO<sub>2</sub> concentration during periods of primary building occupancy, according to the following model, derived from ASHRAE Standard 62-1989:

$$R_{ACH} = \frac{R_i}{C_s - C_o} \frac{N}{V_b}$$

where  $R_{ACH}$  = ventilation rate due to outside air, in ACH;  $R_i$  = individual rate of CO<sub>2</sub> emission, 18 l/h;  $C_s$  = concentration of CO<sub>2</sub> in the conditioned space;  $C_o$  = concentration of CO<sub>2</sub> in the outside air;  $N$  = number of building occupants;  $V_b$  = volume of conditioned space.

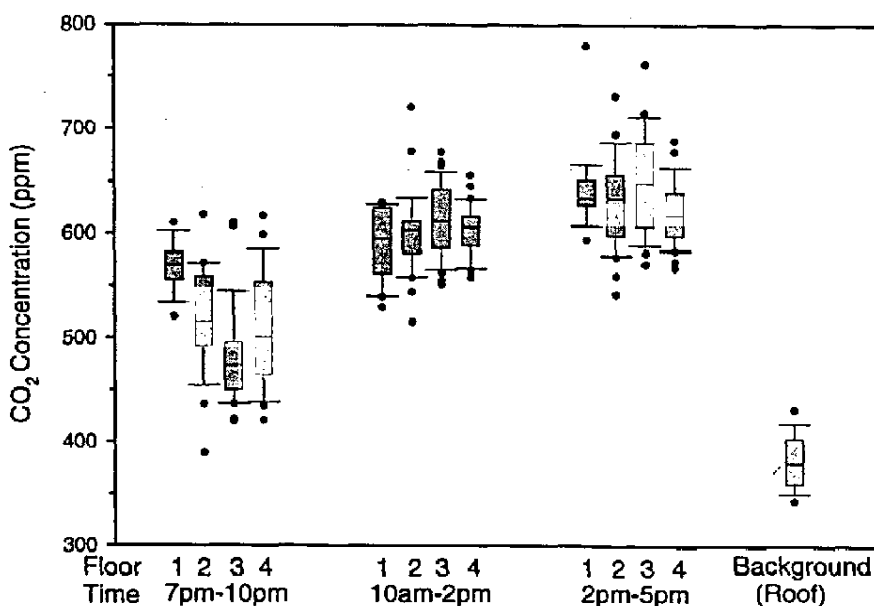


Figure 1. CO<sub>2</sub> concentration for morning, midday, and afternoon for each floor. Also shown is the background (roof) concentration. The bottom and top of the box represent the 25th and 75th percentiles, respectively. The line within the box marks the median. Whiskers above and below the box indicate the 90th and 10th percentiles. In addition, the outlying values are represented by the solid dots.

For 300 occupants in a conditioned space of 1,225,000 ft<sup>3</sup> (the volume of the building less that of the computer facility that was separately ventilated), with an average 10 am–5 pm concentration of CO<sub>2</sub> inside the building of 617 ppm, and an outside concentration of 389 ppm, the estimated air exchange rate was 0.68. Subsequent to these measurements, the ventilation air flow rate was determined by direct air flow measurement in the building HVAC system. Outside air flow was determined to be lower than the design level, or 13,136 cfm. This actual outside air flow corresponded to an overall building air exchange rate of 0.64 ACH, close to the 0.68 ACH estimate from the CO<sub>2</sub> concentrations. A missing panel in the HVAC system was believed to have resulted in the lower outside air flow.

#### Area Concentrations of ETS

A total of 96 area samples were collected and analyzed for respirable particulates (RSP), combustion-derived particulates (UVPM and FPM), ETS-specific particles as solanesol-related particulate matter (Sol-PM), and two vapor phase markers of ETS: nicotine and 3-EP. Ninety-three of the 96 samples were considered usable. The three unusable samples were from the background samples acquired on the building roof, and were considered unusable either due to the pump being blown over in high winds and the sample lost, or contamination from a building air exhaust, making it unsuitable for a background determination. Six remaining outdoor background RSP levels averaged 21.6  $\mu\text{g}/\text{m}^3$ , with average UVPM and FPM concentrations being 6.5 and 3.3  $\mu\text{g}/\text{m}^3$ , respectively. Two

of the six usable samples contained traces of solanesol, but none contained measurable amounts of 3-EP or nicotine.

As expected, the range of concentrations of ETS components was much greater for areas occupied by smokers, than those for areas occupied by nonsmokers. This is illustrated in Figures 2 and 3 for ETS particles as Sol-PM and nicotine. Cubicles and offices occupied by smokers exhibited higher levels and greater variations in ETS concentrations. For example, median nicotine concentration in cubicles occupied by smokers was 2.53  $\mu\text{g}/\text{m}^3$ , compared with that measured in cubicles of nonsmokers, 1.58  $\mu\text{g}/\text{m}^3$ . It is interesting to note that even lower levels (median of 0.38  $\mu\text{g}/\text{m}^3$ ) of nicotine were observed in the offices of nonsmokers, and there was a much greater difference between the median nicotine levels observed for offices occupied by smokers (5.5  $\mu\text{g}/\text{m}^3$ ) versus offices occupied by nonsmokers. The area concentration data are summarized in Table 1, and document an important observation from this study: despite the fact that smoking was unrestricted (except for the computer and mail rooms) throughout the facility, there clearly exist different types of microenvironments, where ETS levels are higher or lower than those found in other microenvironments within the facility. (Note that while 95th percentiles are reported for all data sets, caution should be exercised when considering the relevance of this value for data sets with less than 10 data points.) The bulk of the samples was collected in cubicles and offices occupied by smokers and nonsmokers. Additional sample areas included a break room (community area), the conference rooms used as a staging area for

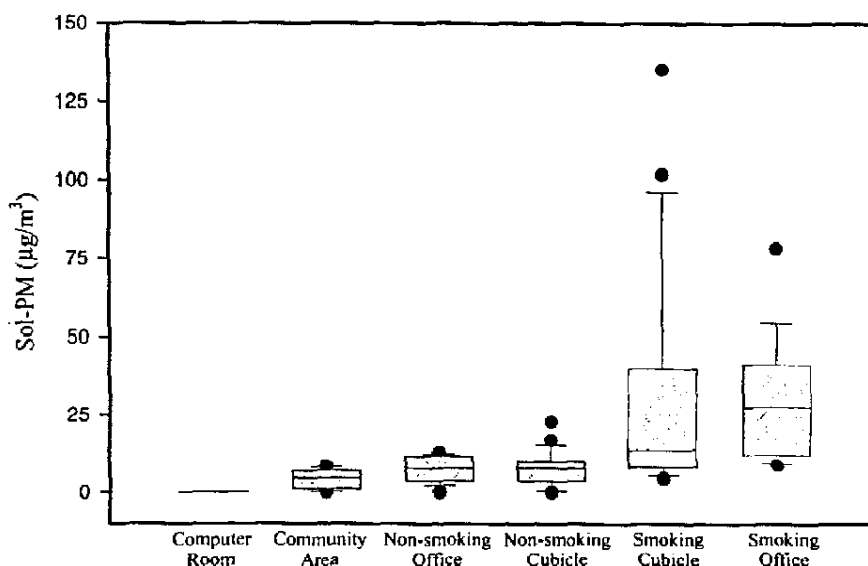


Figure 2. Concentrations of ETS-specific particles as Sol-PM, as a function of sampling location, for area samples. Box plot features are the same as those in Figure 1.

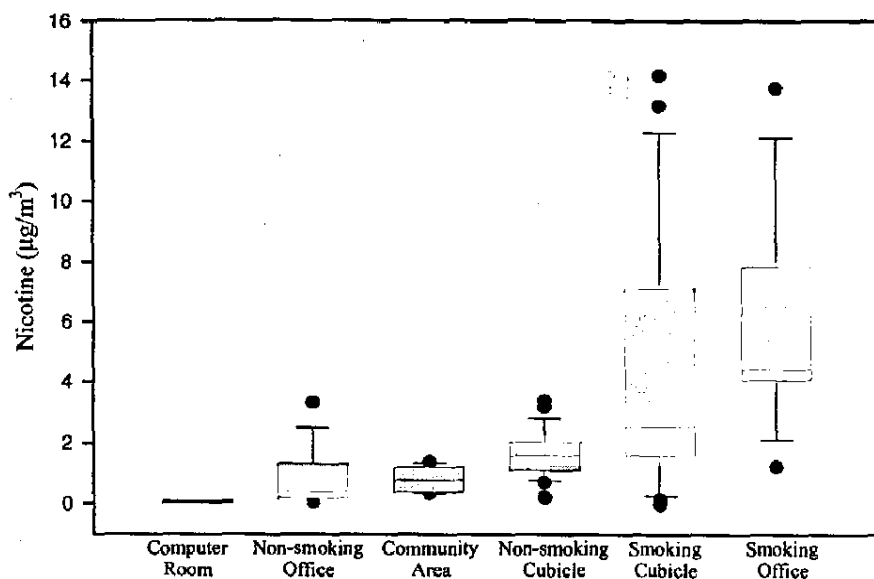


Figure 3. Concentrations of nicotine, as a function of sampling location, for area samples. Box plot features are the same as those in Figure 1.

sampler assembly and flow measurement (where smoking was prohibited during the course of the study when sampling pumps were present), and the computer room. ETS levels in these latter areas tended to be lower, likely due to prohibition on smoking (setup room for this study), lower occupancy (break room), or special ventilation and filtration (computer room). The computer room had a relatively low design air exchange rate (0.27 ACH), relative to the rest of the building, and this, coupled with the use of particle scrubbing filters on separate air cooling units, resulted in much lower levels of ETS particles and vapors than in the remainder of the building.

For the remainder of the data sets, some interesting features were observed. First, considering the ETS-specific constituents solanesol, nicotine, and 3-EP, the ratio of the 95th percentile value to the median value, an indicator of the spread of the results, was quite variable, depending on the constituent and the location. For example, the ratio ranged from 1.3 to 7.1 in offices occupied by nonsmokers. Secondly, we found that in several samples, the quantity of FPM exceeded the apparent quantity of total RSP. UVPM and FPM have been employed as markers for the combustion-derived fraction of RSP. FPM (and UVPM) is really a calculated value, in which the fluorescence response in an analysis of particulate matter is related to the quantity of RSP present in the air. For air in which the only particles present are those generated from cigarette smoke (a situation that would only exist in a controlled atmosphere chamber), all of the particles are combustion-derived, and thus, FPM is numerically equal to RSP. By definition, the FPM value cannot be greater than the RSP value. However, because cigarettes, compared with cigars and pipes, are the

most important contributor to ETS, most marker studies have been directed toward the determination of FPM/RSP conversion factors from cigarette-generated ETS (e.g., Martin et al., 1997). A very recent study by Nelson et al. (1999) has indicated that conversion factors for cigar-generated ETS are much different from those determined from cigarette-generated ETS. Use of conversion factors from cigarette-derived ETS to estimate the contribution to cigar-derived FPM may result in an overestimation of FPM by as much as 44%. To determine if cigar-generated ETS may have played a role in unexpected high FPM/RSP ratios, an analysis of the locations, where samples were acquired that had both RSP levels greater than  $50 \mu\text{g}/\text{m}^3$  and FPM/RSP ratios greater than 1.2, was conducted. Most of these samples were found to have been collected at locations in or very near areas where known cigar smokers frequented. Thus, while the presence of cigar smoke may not be completely responsible for apparently high FPM/RSP ratios, this finding provided credence to the hypothesis that cigar smoke-derived ETS may contribute to the observed ratios.

While there have been a number of studies that have examined area concentrations of ETS (e.g., as cited in Jenkins et al., 2000), recent studies of area measurements of ETS concentrations in unrestricted smoking workplaces have been limited. Oldaker et al. (1995) reported medians of RSP, UVPM, FPM, and nicotine in samples collected from 20 offices in each of two buildings where smoking was unrestricted. Ranges of median values were 30–34, 16–26, 14–15, and 1.8–2.3  $\mu\text{g}/\text{m}^3$ , for RSP, UVPM, FPM, and nicotine, respectively. Such levels are very comparable to those reported in our study (see below). Sterling et al.

**Table 1.** Summary of 8-h time-weighted average (TWA) concentrations (area monitor samples).

Sample category	Number of samples	Number of locations		8-h TWA concentration ( $\mu\text{g}/\text{m}^3$ )					
				RSP	UVPM	FPM	Sol-PM	Nicotine	3-EP
Setup room	6	2	Median	19.6	5.8	4.7	2.1	0.16	0.44
			Mean	17.0	5.6	4.7	2.1	0.17	0.44
			80th Percentile	22.6	6.8	5.9	3.6	0.25	0.60
			95th Percentile	24.5	7.0	6.5	3.9	0.27	0.60
Community area	6	3	Median	30.2	10.5	10.0	4.7	0.75	0.71
			Mean	25.0	10.6	10.0	4.3	0.79	0.69
			80th Percentile	31.1	13.1	13.9	6.9	1.21	0.79
			95th Percentile	32.1	14.7	14.6	8.3	1.37	0.98
Computer room <sup>a</sup>	3	1	Median	19.5	4.2	2.0	0	0.04	0.24
			Mean	23.8	3.9	2.2	0	0.05	0.24
			80th Percentile	42.7	4.3	2.7	0	0.10	0.31
			95th Percentile	42.7	4.3	2.7	0	0.10	0.31
Cubicles occupied by nonsmokers	30	12	Median	28.3	14.4	15.4	7.7	1.58	0.88
			Mean	29.2	14.9	15.7	7.7	1.65	0.83
			80th Percentile	37.3	19.4	21.1	10.3	2.15	1.07
			95th Percentile	43.1	22.9	26.1	16.5	3.02	1.18
Offices occupied by nonsmokers	12	4	Median	23.8	10.6	10.3	7.6	0.38	0.71
			Mean	25.4	11.6	12.2	7.3	0.90	0.65
			80th Percentile	31.3	15.6	16.8	11.7	1.37	0.83
			95th Percentile	43.2	16.7	19.0	12.3	2.68	0.92
Cubicles occupied by smokers	18	6	Median	37.9	20.0	23.1	13.6	2.53	1.02
			Mean	45.9	43.3	53.8	32.2	4.23	1.25
			80th Percentile	61.1	68.0	88.5	51.2	7.66	1.83
			95th Percentile	105.4	132.7	180.4	106.9	13.33	2.99
Offices occupied by smokers	12	4	Median	46.4	44.1	71.1	27.5	5.5	1.8
			Mean	43.9	54.9	91.6	29.5	6.5	2.1
			80th Percentile	55.0	70.2	135.3	44.1	8.5	2.6
			95th Percentile	75.2	112.2	217.7	59.6	12.64	3.93
All cubicles and offices	72	26	Median	29.9	16.8	18.7	9.6	1.83	0.91
			Mean	35.2	28.1	37.3	17.4	2.99	1.12
			80th Percentile	46.1	34.4	34.4	18.8	4.35	1.36
			95th Percentile	81.9	106.1	176.1	78.2	11.7	2.87
All area samples excluding background	87	29	Median	28.9	14.7	15.2	8.2	1.5	0.83
			Mean	32.9	24.5	31.9	14.8	2.5	1.01
			80th Percentile	42.7	27.6	32.3	16.6	3.8	1.21
			95th Percentile	66.0	85.2	147.0	58.7	8.73	2.61

<sup>a</sup>No smoking permitted in the computer room.

(1996) examined both area and personal exposure ETS levels in two buildings where smoking was unrestricted. Area samples were collected in each building at two locations 4 days in succession. For the combined data set ( $N=16$ ), median concentrations were 23, 3, 1.65, <2.1, 2.1, and 0.9  $\mu\text{g}/\text{m}^3$  for RSP, UVPM, FPM, Sol-PM, nicotine, and 3-EP, respectively. These values compare with the combined office and cubicle data ( $N=72$ ) for our study of median concentrations of 30, 17, 19, 9.6, 1.83, and 0.91  $\mu\text{g}/\text{m}^3$ . The comparison suggests that the vapor phase marker levels for this study are comparable, whereas the particle phase marker concentrations are somewhat greater. Ham-

mond et al. (1995) reported area measurements of ETS nicotine in a variety of occupational settings. For the subset of sampling locations most comparable to those collected for this study (125 samples collected in open offices of nonsmokers in unrestricted smoking workplaces), median nicotine concentration was reported to be 8.6  $\mu\text{g}/\text{m}^3$  (90th percentile: 34  $\mu\text{g}/\text{m}^3$ ). These values compare to a median and 90th percentile concentrations in this study for cubicles and offices of nonsmokers ( $N=42$ ) of 1.48 and 2.75  $\mu\text{g}/\text{m}^3$ , respectively. However, the method of calculation of concentration levels in the Hammond study has been called into question (Ogden, 1996; Ogden and Jenkins, 1999;

Daisey et al., 1998), such that values reported in Hammond et al. (1995) may overestimate the actual concentrations by as much as a factor of 3.7. If the Hammond data are corrected for the entire magnitude of the calculation error, the median value is closer to that reported in this study, but the corrected 90th percentile value is still a factor of 3 greater than that reported for this study.

#### Personal Exposure to ETS

Seventy-two 8-h personal exposure samples were collected, one on each of three successive days by each of the 24 subjects. Examination of the cumulative distributions of the 8-h TWA concentrations (Figure 4) indicates that the levels encountered varied over a relatively narrow range. For example, the interdecile ranges (10th–90th percentile) for RSP, FPM, and 3-EP were less than one order of magnitude, and those of nicotine and Sol-PM were less than a factor of 20. Note that about the 30th percentile, the distributions of the 3-EP and nicotine values shift their relative positions. That is, at the lower ETS concentrations, the nicotine/3-EP ratios are less than 1, whereas at higher levels, they are greater than 1. This was the case for 26% of the personal exposure measurements in this study. The ratio had a strong linear functionality with nicotine concentration ( $R=0.87$ ). Analysis of 8-h personal exposure levels of subjects in our 16 Cities Study (Jenkins et al., 1996), who worked in office settings where smoking was confirmed to occur, indicated that 27% of the nicotine/3-EP ratios was less than 1. Martin et al. (1997) have reported sales-weighted ETS emission data for a number of US cigarette brands, and the ratio of nicotine/3-EP was reported to be 2.45. However, these studies were conducted in stainless steel chambers, an environment totally

unrelated to the office environment reported here. (Note that Daisey et al., 1998 reported a ratio for six US brands of 1.4. However, that study was not performed on true human-generated ETS, but rather aged and diluted sidestream tobacco smoke only.) We can only conjecture as to the reason for this phenomenon, but speculate it is likely due to the differences in adsorption/reemission properties of the two constituents at this particular air exchange rate (Nelson et al., 1992; Ogden and Jenkins, 1999).

A summary of personal exposure measurements is provided in Table 2. Two individuals who worked in more isolated areas of the facility had the lowest 8-h exposures. Median concentrations to which nonsmoking workers occupying offices were exposed were somewhat lower than those of workers occupying cubicles, although differences were less apparent at the upper ends of the distributions. Overall, the highest levels of nicotine were observed in the cubicles, which were open environments.

The impact of subject-reported smoker proximity on personal exposure to combustion-derived and ETS-derived constituents was examined, and the results are reported in Table 3. In this environment, apparent proximity to one or more smokers had only a modest (~50% increase) impact on personal exposure concentrations, with the exception of nicotine. In that case, proximity increased median 8-h TWA concentrations by 2.5-fold. We speculate that this may be due to adsorption and reemission of nicotine on nearby surfaces (e.g., Ogden and Jenkins, 1999), but such a hypothesis could not be tested with this experimental design.

There was no intentional congruence between the area sampler placement and the primary work locations of the

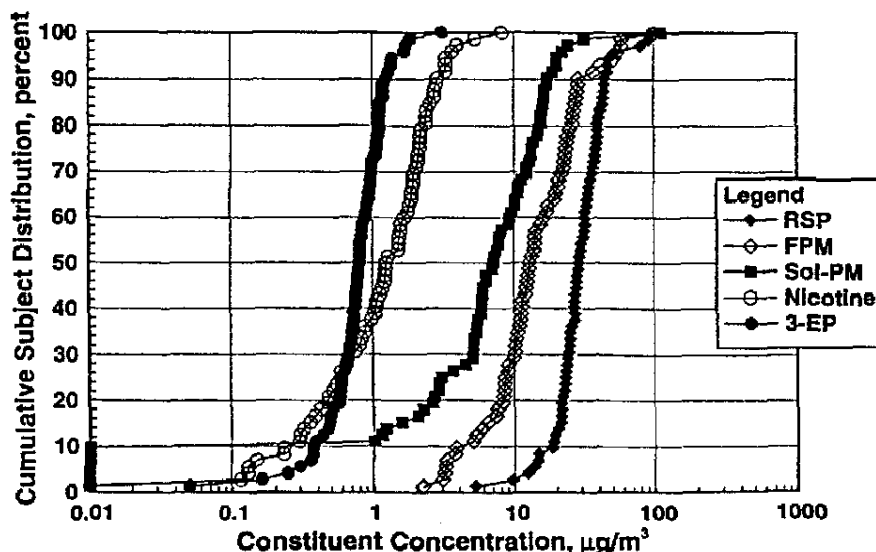


Figure 4. Cumulative distribution of personal exposure concentrations for all subjects.

Table 2. Summary of 8-h TWA concentrations (personal monitor samples).

Subject's primary workplace	Number of samples	Number of subjects		8-h TWA concentration ( $\mu\text{g}/\text{m}^3$ )					
				RSP	UVP	FPM	Sol-PM	Nicotine	3-EP
Cubicle	48	16	Median	31.6	16.4	16.7	9.4	1.82	0.87
			Mean	33.5	18.7	20.7	10.3	1.95	0.97
			80th Percentile	42.4	22.2	27.7	16.3	2.68	1.17
			95th Percentile	52.0	42.4	54.5	21.9	3.88	1.69
Office	18	6	Median	26.4	11.0	12.3	6.5	0.70	0.69
			Mean	29.4	16.1	16.9	12.2	0.96	0.70
			80th Percentile	35.8	18.6	22.3	12.2	1.5	0.97
			95th Percentile	79.4	90.7	100.3	111.3	3.22	1.07
Computer room <sup>a</sup>	3	1	Median	27.6	4.0	3.1	0	0.23	0.30
			Mean	26.7	4.4	2.8	4.4	0.25	0.30
			80th Percentile	28.0	6.0	3.2	13.1	0.38	0.37
			95th Percentile	28.0	6.0	3.2	13.1	0.38	0.37
Mail room <sup>a</sup>	3	1	Median	26.6	4.5	3.7	0	0.13	0.38
			Mean	26.0	4.7	3.5	0	0.13	0.42
			80th Percentile	36.7	6.1	3.8	0	0.15	0.51
			95th Percentile	36.7	6.1	3.8	0	0.15	0.51
All personal monitor samples	72	24	Median	28.8	14.1	13.0	7.1	1.24	0.80
			Mean	31.9	16.9	18.3	10.1	1.56	0.85
			80th Percentile	38.9	22.0	26.1	15.5	2.35	1.10
			95th Percentile	52.0	42.4	54.5	21.9	3.58	1.65

<sup>a</sup>No smoking permitted in the computer or mail rooms.

subjects. Results of at least one workplace study (Maskarinec et al., 2000) — albeit in much different environments — have indicated poor agreement between individual personal monitor concentrations of ETS and those collected from nearby stationary area samplers, but good agreement between pooled data sets. For this study, when the data set is taken as a whole, median personal exposure concentrations were in good agreement with median area concentrations. Comparison of the last categories in Tables 1 and 2 reveals few important differences in the median concentrations of constituents. At the 95th percentile of the distribution, area concentrations were distinctly higher. For one subject where an area monitor was coincidentally located at his cubical space, area concentrations were a factor of 2–3 times higher

on two of the 3 days of the test, and a factor of 1.5–3 times lower on the final day.

A comparison of personal monitoring data acquired in this study with that obtained from a subset of subjects in another study (Jenkins et al., 1996), both groups having worked in unrestricted smoking workplaces, reveals some differences in 8-h TWA concentrations (Table 4). Overall, with the exception of RSP, median concentrations in this study were somewhat greater, whereas mean concentrations (more likely to be impacted by extremes of the distributional values) were lower. There are likely to be a number of causes for the differences. First, in the 16 Cities Study, a variety of workplaces were reported by the subjects: only 55% of the subjects reporting no smoking restrictions

Table 3. Impact of smoker proximity on personal exposure to selected ETS constituents.

		8-h TWA concentration ( $\mu\text{g}/\text{m}^3$ )			
		FPM	Sol-PM	Nicotine	3-EP
Subjects reporting no smokers within 25 ft ( $n=21$ )	Median	10.9	5.3	0.66	0.57
	Mean	10.6	6.1	0.83	0.63
	80th Percentile	17.2	10.6	1.54	0.95
	95th Percentile	21.5	17.1	2.11	1.17
Subjects with one or more smokers within 25 ft ( $n=51$ )	Median	15.2	7.8	1.64	0.84
	Mean	21.5	11.7	1.85	0.95
	80th Percentile	27.7	16.0	2.68	1.11
	95th Percentile	56.2	23.0	3.73	1.67

worked in office buildings. In addition, the distributional extremes (e.g., 95th percentile) in the former study were much higher than those in this study.

An important observation from this study relates to substantial differences in the apparent relative contribution of ETS-derived particles (Sol-PM) to the overall level of RSP. Throughout the entire distribution, the relative contribution of ETS to RSP is greater than that for comparable subjects in the previous study (see Table 4), but the difference is most pronounced at the median level. In this study, at the median level, ETS-derived particles comprised 25% of the total RSP. This finding is not due to the differences in detection limits between the two studies. In the earlier study, 39% (53 of 136 subjects in unrestricted smoking workplaces) of the personal exposure samples had Sol-PM levels below the 8-h limit of detection (LOD) of  $0.280 \mu\text{g}/\text{m}^3$ , versus only 18% (13 of 72) in this study, even though the LOD in *this* study was greater by a factor of 9 ( $2.56 \mu\text{g}/\text{m}^3$ ). Such is not likely due to any substantial differences in the analysis of solanesol between the two laboratories that performed the analyses. Results of a major interlaboratory comparison study (Ogden, 2000) demonstrated that both laboratories were in good agreement for the analysis of solanesol. (Our laboratory exhibited a mean relative percentage difference from the mean of all 11 collaborating laboratories of  $-11.2\%$  for solanesol.) We suspect that the difference may be due to either different sampling head components or configuration, or light sensitivity of solanesol, which may result in diminished postcollection degradation of solanesol. In the earlier study (16 Cities Study; Jenkins et al., 1996), particulate samples were collected on  $1.0\text{-}\mu\text{m}$  pore size PTFE filters packed in clear polystyrene filter holders (Millipore M000037A0). Upstream of the filter was a nylon cyclone vortex assembly, designed to pass 50% of the particles  $3.5 \mu\text{m}$  in diameter. In this study, particles were collected on the same filter, housed in a black opaque conductive plastic holder, upstream of which was a

conductive plastic cyclone (BGI-4CP Respirable Dust Cyclone). A careful experimental study reported by Ogden and Richardson (1998) demonstrated postsample collection degradation of solanesol in the clear filters used in the earlier study when exposed to extreme lighting conditions. However, no discernable degradation occurred when chamber-generated ETS particles were collected on such filters/holder assemblies and worn by subjects under workplace and away-from-work conditions designed to mimic those encountered in personal monitoring studies. Nevertheless, the authors recommended the use of opaque black filter holders in future studies. That recommendation was followed for this study. We speculate that in the 16 Cities Study (Jenkins et al., 1996), either interactions of solanesol with light under the sampling conditions used, or between solanesol and the nylon vortex cyclone and/or the clear plastic filter holder, may have contributed to reduced collection efficiency and/or stability of solanesol on the PTFE membrane. However, a specific experimental investigation designed to test the hypothesis would be required to confirm or refute the speculation, and such was beyond the scope of the study being reported here. It should be noted that Phillips et al. (1997) reported an ETS contribution to RSP in smoking workplaces of 39% in the city of Barcelona. This was the highest fractional contribution reported by the authors in the series of studies conducted in Europe, Asia, and Australia.

One of the important aspects of this study was the ability to assess the variability in ETS levels over the 3-day sample collection period, both for the area samples and the personal monitoring samples. To our knowledge, this is the first time repeated measurements have been made for workplace personal exposure measurements using modern markers for indicators of ETS concentrations. The day-to-day variations in individual area samples at a particular location and that of personal monitoring samples for an individual subject are presented in Table 5. The variability was measured in terms of mean relative standard deviation, and

**Table 4.** Comparison of 8-h TWA concentration of ETS components [this study (all subjects) versus 16 Cities Study subjects working in unrestricted smoking workplaces].

Study	Number of samples	Number of subjects		8-h TWA concentration ( $\mu\text{g}/\text{m}^3$ )						Sol-PM/RSP ratio
				RSP	UVP	FPM	Sol-PM	Nicotine	3-EP	
16 Cities Study <sup>a</sup>	136	136	Median	40.9	9.6	7.7	0.9	1.02	0.50	0.031
			Mean	61.7	26.9	25.2	16.1	3.36	1.44	0.166
			80th Percentile	74.7	31.6	27.5	14.2	4.58	1.77	0.282
			95th Percentile	180.6	105.4	102.4	87.8	14.90	6.02	0.773
This study	72	24	Median	28.8	14.1	13.0	7.1	1.24	0.80	0.250
			Mean	31.9	16.9	18.3	10.1	1.56	0.85	0.333
			80th Percentile	38.9	22.0	26.1	15.5	2.35	1.10	0.553
			95th Percentile	52.0	42.4	54.5	21.9	3.58	1.65	0.888

<sup>a</sup>Jenkins et al. (1996).

Table 5. Relative precision estimates: area and personal monitoring samples (selected ETS constituents).

Area or personal monitor samples	Number of locations/subjects	Average relative precision <sup>a</sup> (%)					
		RSP	UVP	FPM	Sol-PM	Nicotine	3-EP
Area samples	29	32.9	24.8	28.2	58.9	42.1	26.5
Personal samples	24	33.5	26.6	30.6	62.5	39.0	19.7

<sup>a</sup>Also known as "relative standard deviation" and "coefficient of variation." The precision estimates were obtained by dividing the standard deviation by the mean for each area/subject and multiplying by 100%.

the values ranged from 20% to 60%. In general, the variability was less than 50%, with the exception of Sol-PM. As shown in Table 5, the area sample and personal monitoring sample variabilities for all constituents were very comparable, with usually less than 10% difference between the area and personal values. Because the personal and area sample variabilities are consistent, this suggests that the data are a fairly good representation of the day-to-day variation in ETS levels observed in this study. It should also be noted that the personal habits of the subjects and the smokers around them in this unrestricted smoking workplace will influence the daily variability. While the number of subjects is not large, the low variability suggests that workplace risk assessments performed on larger data sets (e.g., the 16 Cities Study), where individual exposure was determined only on a single day, may be more generalizable to overall workplace exposures. However, such would have to be confirmed on a larger group of subjects in less homogeneous environments.

## Conclusions

Even in a large facility where the air is mixed more than three times per hour, the range of ETS concentrations encountered within various microenvironments was considerable. For example, 8-h TWA concentrations of ETS-specific particles ranged from undetectable up to  $135 \mu\text{g}/\text{m}^3$ . Nicotine ranged from undetectable up to  $>14 \mu\text{g}/\text{m}^3$ . Strict comparison of this data set with those of other studies is difficult because of the limited number of studies conducted in office settings where smoking is truly unrestricted. Median levels for nicotine in this study are comparable to those determined by Sterling et al. (1996), and lower than those reported by Hammond et al. (1995). Hedge et al. (1994) reported ETS constituent levels in several facilities where smoking restrictions were in force, and generally found much higher levels in those areas where the monitoring was conducted. In this latter study, samplers were deliberately located in densely occupied sites within the building. However,  $\text{CO}_2$  levels in that study were comparable to those observed in this study, suggesting that the density of occupants was not dramatically higher than that in our study.

This is the first study of which the authors are aware where daily sequential personal exposure to ETS in the

workplace has been reported. Daily variation ranged from ca. 20% to 60%, depending on the constituent. Eight-hour TWA exposures to ETS were somewhat lower for non-smoking workers that occupied offices, when compared with those occupying cubicles. This may reflect proximity to the primary source of ETS components and the impact of a less open environment. However, while regular proximity to smokers may increase exposures on an individual basis, on a group basis, the impact appeared to be relatively modest. When compared with another large study of individuals working in unrestricted smoking workplaces (Jenkins et al., 1996), median 8-h TWA levels of tobacco-specific and combustion-derived constituents were somewhat higher for this study, but RSP levels were lower. [It should be noted that concentrations of ETS-specific particles (as Sol-PM) may not be strictly comparable with earlier studies due to differences in field sampler holder configuration, which may enhance postcollection stability of solanesol.] However, the overall levels of ETS to which these workers were exposed were considerably lower than those estimated by OSHA to be present in offices where smoking is unrestricted (USDOL, 1994). For example, OSHA estimated the range of average office concentrations of nicotine to be  $2\text{--}10 \mu\text{g}/\text{m}^3$ , with considerably higher maximum values. In this study, average 8-h TWA personal exposure level of nicotine was  $1.52 \mu\text{g}/\text{m}^3$ , and the 95th percentile level was  $3.58 \mu\text{g}/\text{m}^3$ , indicating that OSHA's estimates are not reflected by the situation observed in this unrestricted smoking facility.

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